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14. ABSTRACT

This report results from a contract tasking Heriot-Watt University as follows: The project will use femtosecond laser machining to create comb-like micro-structures from GaAs wafers that can be combined to produce a suitably oriented pattern for QPM. Readily available GaAs wafers will be used and the study will concentrate on evaluating: (a) the quality of femtosecond machining possible in GaAs in terms of its repeatability, precision and surface finish; (b) the feasibility of aligning two GaAs combs in intimate optical contact; (c) the transmission loss of the composite sample, and; (d) second-harmonic generation for a 2.3µm input wavelength from an existing OPO source. The project wil utilise a £250k amplified Ti:sapphire laser that has been recently commissioned at Heriot-Watt University. An existing 2.3µm modelocked OPO will be used for optical testing purposes. Funding is requested for GaAs wafers, optics, a contribution to research / technical staff time and an optical alignment system to permit precise contacting of the GaAs combs. Derryck Reid is the principal investigator. Dr Reid will be supported by a PhD student, Mr Stuart Campbell, who holds a BSc (Heriot-Watt University) and an MSc in Optoelectronics (St Andrews University) and by a research assistant Mr Euan Ramsay (M.Phys., St Andrews University)

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FEMTOSECOND LASER MACHINING OF GALLIUM ARSENIDE WAFERS FOR THE CREATION OF QUASI-PHASEMATCHED DEVICES

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1. Introduction and review of original project objectives

Gallium arsenide (GaAs) is a semiconductor with a wide infrared transparency (0.87 - 50µm) and an extremely high second-order optical nonlinearity (~80pm V^{-1}). GaAs is a member of the $\bar{4}3m$ point group and has no birefringence therefore it cannot be birefringently phasematched, so compromising its usefulness as a nonlinear material. Quasi-phasematching is the natural solution to the problem of phasematching in GaAs but since GaAs is non-ferroelectric it cannot be periodically poled in the same way as lithium niobate (LN) and potassium titanyl phosphate (KTP). Despite this constraint, other methods could be used to quasi-phasematch GaAs and in our original proposal we suggested a strategy of combining two separate Brewster cut GaAs 'combs' that were machined with a pitch equal to the QPM period (see figure 1.1 opposite).

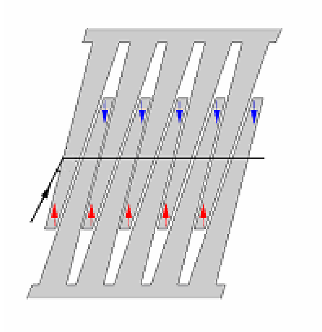

Figure 1.1 schematic of planned device.

An alternative method was also proposed which involved using infrared transmitting UV-setting optical epoxy to create a QPM device using only a single piece of GaAs, machining channels in the GaAs and in-filling the gaps with epoxy. It was thought that this approach would produce a more robust device and eliminate the need for delicate meshing of the "combs". Upon conducting tests on commercially-available epoxy we found that its transparency in the thicknesses required was too low to make its use practical in our devices. We also found that the index of the available epoxies was too low to allow efficient optical propagation through a composite GaAs:epoxy device since the Fresnel losses would have been large for at least one of the polarisations involved in a QPM interaction. Early in the project it was therefore decided to concentrate on creating intermeshing comb structures, however the in-filling approach may in fact be viable using high index chalcogenide glasses (see Section 7.3 for further details).

2. QPM device design

We decided to aim to construct QPM devices that would frequency double laser light at wavelengths of λ=10.6µm and λ=2.3µm because sources at these wavelengths are available at Heriot-Watt. Our design considerations were therefore based around these wavelengths and their second-harmonics at λ=5.3µm and λ=1.15µm.

A number of different equations was sourced to describe the dispersion of GaAs, all of which agreed with each other at short wavelengths (λ< 2.0µm) but only two of which continued to agree at longer wavelengths (λ~9.0-11.0µm). Only one of these equations was verified experimentally by the authors at very long wavelengths (up to λ=50µm) and this equation was chosen as the basis of our model. Using the Sellmeier data from [1] a dispersion curve for GaAs was constructed and this is shown in Figure 2.1 opposite.

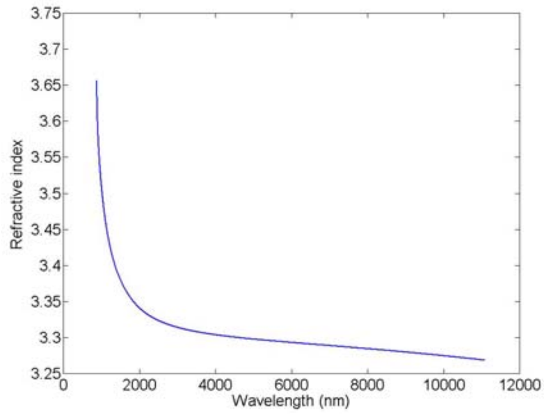

Figure 2.1 Dispersion curve for GaAs

This dispersion curve was used to determine that the coherence length of the SHG interaction for 2.3µm to 1.15µm in GaAs would be 4.88µm and that the coherence length of the SHG interaction for 10.6µm to 5.3µm would be 137µm. Given the mechanical properties of GaAs, it was believed that a 4.88µm wide finger would not be structurally sound. Although it would have been possible to build a 3 or 5 period finger (i.e. 14.64µm or 24.4µm), even a finger 25µm wide may have been too delicate to handle and thus it was decided to initially attempt to machine the structure with a 137µm coherence length.

The length of the initial GaAs device was decided by considering the experimental constraints associated with testing the device using a quasi-CW λ=10.6µm CO_2 laser. The optics for focusing the beam must be kept to a short focal length (max 50mm) to yield the high fluence necessary for efficient nonlinear conversion. At a wavelength of 10.6µm this results in a short confocal parameter dictating that the final device must be less than 2mm in length, implying a device with 5 fingers per comb giving a total length of 1.37mm.

3. Machining

3.1 Experimental configuration and calibration of machining focal position

The femtosecond machining system was centred around a commercial 5kHz regenerative amplifier (Spectra Physics Hurricane), a single unit comprising CW and Q-switched pumps for an oscillator and regenerative amplifier respectively. The entire system was Ti:sapphire-based and capable of producing pulses of duration 140fs and maximum energy of 200µJ at a central wavelength of 800nm.
Figure 3.1 shows a schematic of the experimental configuration.

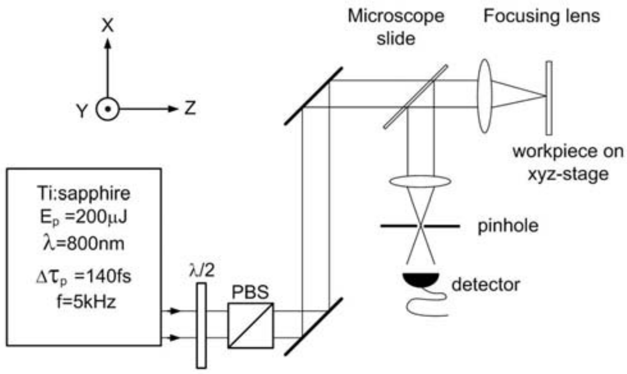

Fig 3.1 Schematic of laser setup.

A combination of a polarising beamsplitter (PBS) and a half-wave plate (λ/2) allowed the average power at the sample to be smoothly varied over 3 orders of magnitude with controllable machining possible even for pulse energies of less than 200nJ. The pulse length was monitored by a single shot autocorrelator. The beam from the amplifier was horizontally polarised but was not perfectly diffraction-limited and was measured to have an M^2 value of 1.3 in the horizontal and vertical directions and a $1/e^2$ beam radius of 3.2mm around 50cm from the output aperture. The output of the laser was focused onto the GaAs sample surface by using one of a variety of bulk optics and long focal length microscope objectives:

- Mitutoyo M-plan NIR-corrected of numerical aperture 0.55.
- Mitutoyo M-plan NIR-corrected of numerical aperture 0.26.
- 75mm focal length AR coated achromatic doublet of numerical aperture 0.043

The different focusing lenses were capable of achieving a minimum focal spot size (in air) of around 727nm, or a maximum confocal parameter of 522µm depending upon the choice of lens.

The purpose of the first part of the machining study described here was to investigate surface ablation. It was therefore important to know with good precision the position of the beam focus relative to the workpiece surface. This would also be critical due to the high NA (and consequently small confocal parameter) of the high power machining objective. To find the correct focal position for the workpiece, a program written in the Agilent VEE environment was used to scan the sample mounted on translation stages through the focus in 5µm steps in the z direction and simultaneously measure the power of the reflected light after a lens and pinhole combination. The pinhole was placed confocal to the focused spot at the sample. The positioning of the pinhole was critical in order to ensure that the highest voltage on the detector was only recorded when the focus of the beam coincided with the front face of the sample. For the purpose of finding the correct pinhole position a “trial and error” approach was applied which used a VEE program to raster scan a test sample through the focus of the beam in such a way that an incremental change of the focal position was made after each sweep of the raster. The resultant channels machined in the sample were analysed and the best example of machining was chosen and related back to the specific focal position.

The GaAs wafers were sourced from Wafertec and were in the (100) plane. The wafers were 2inches in diameter and 350µm thick

An optical micrograph of a trench cut with the focus of the beam on the surface of the GaAs is shown in Figure 3.2. This cut was made using a pulse energy of 10µJ, and a pulse repetition rate of 5kHz whilst moving the sample at a rate of 10mm/sec.

In the top half of Figure 3.2, the microscope was focused on the surface of the crystal, showing the edge quality of the cut, one of the properties which demonstrates good machining. The lower part of the figure shows the bottom of the trench in focus, faintly visible are the "milling-like" marks left by the pulses overlapping as the beam moved along the sample, an indicator that the best focal position for machining had been found.

Once the focal position for best machining had been found a new sample piece was placed at this point in the focus and the pinhole adjusted for maximum transmission. Once this alignment process had been completed the method could be consistently utilised to align any new workpiece positioned in the beam by adjusting its focal position to maximise the signal on a photodiode placed after the pinhole.

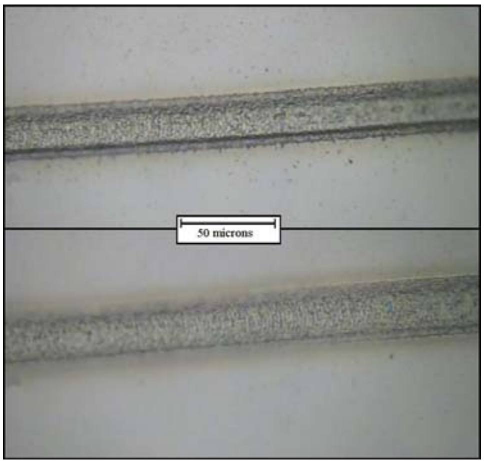

Fig 3.2 Trench cut in GaAs. The upper image is focused on the surface of the wafer and the lower image is focused at the base of the trench.

3.2 Investigation of ablation rates in GaAs

Once the correct focal position had been found the next task was to demonstrate the ability to cut fully through a GaAs wafer which were 350µm thick. The machining of through-slots was achieved by passing the laser focus over the workpiece a number of times.

To produce a series of multiple cuts, a program was written to control the stages to make a linear cut in the GaAs, then increment the sample towards the focus ("z-direction") of the beam by the depth of the resultant trench, which was known from the single cut trench investigations carried out previously. The exact distance that the workpiece needed to be moved depended on the pulse energy used, but was of the order of a micron. The program then made a further cut, incrementing the sample towards the focus once more and so on. The program produced trenches made by 2, 4, 8, 16, 32…512 passes (and sample movements in the z direction) of the laser beam. The resultant wafer had a pattern as illustrated opposite in Figure 3.3.

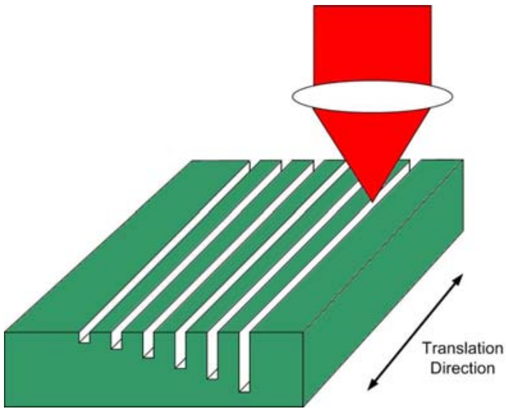

Fig 3.3 Pattern of machining for depth testing

The program was repeated at three pulse energies – 20µJ, 40µJ and 60µJ – to find the optimum cut width and to ensure the wafer could be reliably cut all the way through without causing unwanted damage or an unusable cut profile. The laser repetition rate was kept at 5kHz and the focusing objective had a numerical aperture of 0.26. In each case the scan speed was kept at 10mm/s.

Analysis of the trench widths was performed using an optical microscope which had a calibrated scale. A sample micrograph acquired using this microscope can be seen in Figure 3.4 opposite. The widths of the cuts as measured on the surface of the sample, for different pulse energies and number of cuts, are shown in Figure 3.5 below.

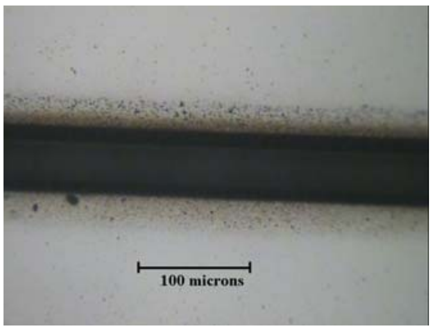

Figure 3.4 – Trench cut using 64 cuts at 60µJ

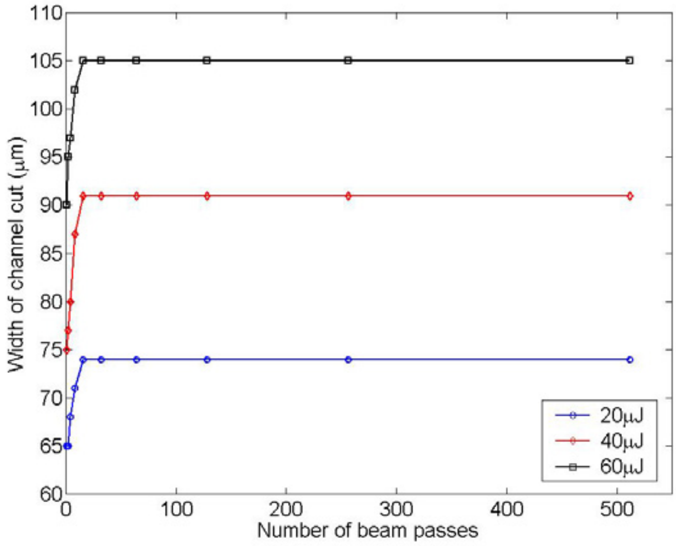

Figure 3.5 – Graph showing different cut widths for different pulse energies and number of cuts

As can be seen from the graph, the cut width at all three pulse energies reached a maximum once 16 cuts had been made across the sample and remained constant no matter how many additional passes were made. This information is particularly useful as we could select a pulse energy to create the width of cut desired irrespective of how many cuts were needed in the sample. The plateaux observed in the graph are a result of the precise ablation threshold associated with femtosecond laser machining; for a given pulse energy and focusing arrangement, beyond a certain beam radius the peak laser intensity falls below the machining threshold and no further ablation can occur, regardless of the number of beam passes that occur.

Unfortunately none of the cuts passed completely through the wafer, with each reaching a maximum of approximately 200µm. This depth limit is caused by the walls of the trench blocking a greater and greater percentage of the beam from the machining, causing each pass to remove slightly less material. This effect is represented pictorially in Figure 3.6. In the left image the focal point is towards the front surface of the workpiece and none of the beam is apertured by the edge of the trench. In the right hand image, however, the lateral extent of the beam is larger than the trench at the front surface of the workpiece and hence the beam undergoes aperturing at the trench entrance. This effect limits the power that arrives at the surface of the material and hence limits the maximum depth of trench.

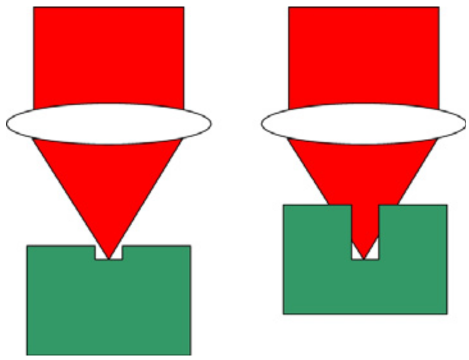

Figure 3.6 – The effect of the trench walls on the power reaching the surface of the workpiece.

To cut all the way through the wafer the lowest power (i.e. largest confocal parameter) focusing optic (75mm achromatic doublet of numerical aperture of 0.043) was used to replace the microscope objective, giving the largest available machining depth of focus of 523µm (greater than the thickness of the wafer). The machining program described earlier was then repeated and the results of the tests that were carried out using the achromatic lens are described below.

The depths of the trenches were measured with the optical microscope by mechanically cutting the wafer and looking down the laser machined trench. The optical micrographs shown below in Figure 3.7 show some examples of the images taken. The view is looking along the trenches, the machining laser beam originates from the left of these pictures. The pulse energy used to create all the trenches in Figure 3.7 was 20µJ.

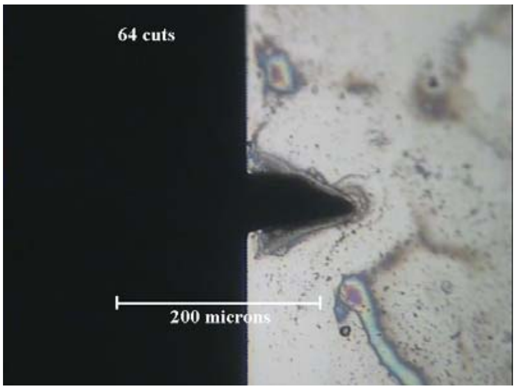

Figure 3.7(a) – Depth achieved for 64 cuts at 20µJ

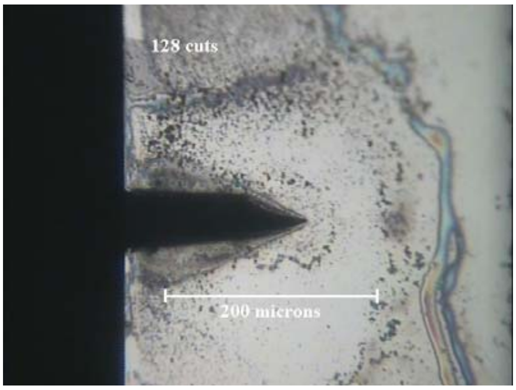

Figure 3.7(b) – Depth achieved for 128 cuts at 20µJ

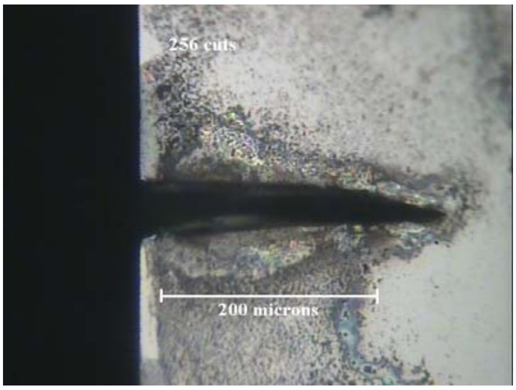

Figure 3.7(c) – Depth achieved for 256 cuts at 20µJ

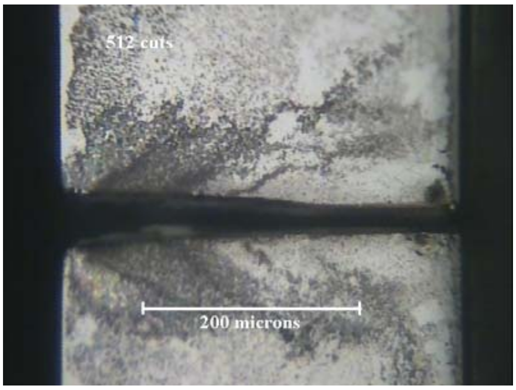

Figure 3.7(d) – Depth achieved for 512 cuts at 20µJ

The debris seen on the GaAs in these pictures is not recast and is not damage to the wafer face. It is some dust from the mechanical diamond saw used to cut the laser machined wafers apart to allow inspection of the trench depths. This is because no suitable cleaning method had been devised to safely remove the dust, due to health concerns about the material. The dust would not be present upon the comb structured devices as no mechanical cutting is necessary.

Figure 3.8 illustrates the depth of machining that was achieved with different pulse energies and different numbers of cuts. As would be expected the trench depths increased with the number of passes and tended towards a limit.

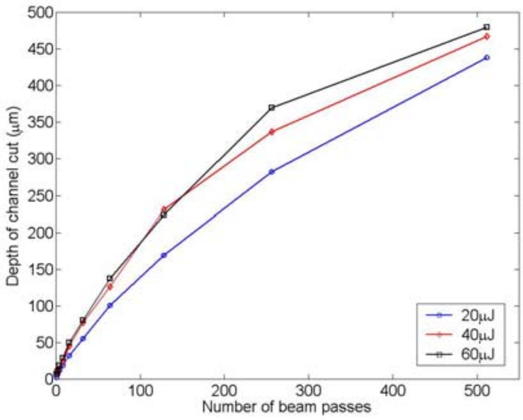

Figure 3.8 – Machining depth for different pulse energies and different numbers of cuts

The departmental scanning electron microscope (SEM) was used to get a more detailed view of the trenches. Two of these micrographs are shown in Figures 3.9(a) & (b) below. Figure 3.9(a) shows the effect of 128 passes at 20µJ pulse energy and Figure 3.9(b) shows the case for 256 passes at 20µJ. The cleaved edge of the wafer shows an extremely square edge relative to the machined trenches, demonstrating that femtosecond machining produces little or no shock wave compared to longer pulse machining and as a result shows negligible unwanted damage to the workpiece.

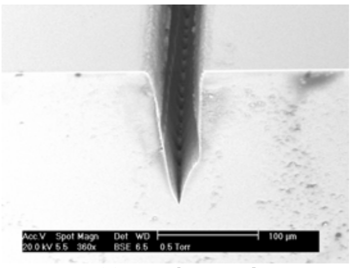

Figure 3.9(a) Trench created using 128 passes at 20µJ

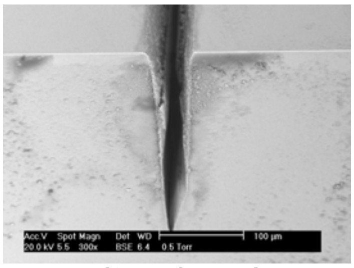

Figure 3.9(b) Trench created using 256 passes at 20µJ

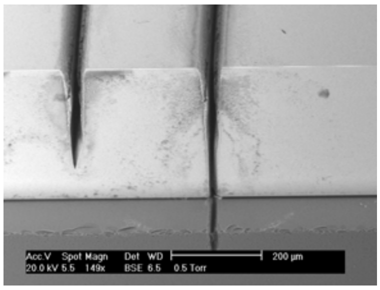

Figure 3.10 trenches cut with 256(left) and 512 passes , at 20µJ pulse energy

In Figure 3.10 the 256 and 512 pass trenches from 20µJ pulse energy are shown. The dark material at the bottom of the picture is the microscope slide to which the wafer was attached. The machining of the 512 passes is clearly visible where the laser has cut all the way through the wafer and into the slide.

Despite reaching depths sufficient to cut through the wafer, the number of cuts was deemed to be too high, taking too long to produce a device. For instance a 5 finger comb with fingers 3mm long would have a beam path length of over 35mm and at 10mm/second scanning speed with 512 passes would have taken approximately 30 minutes to cut. As this time scale was deemed too long to produce a comb, the pulse energy was increased towards the maximum possible pulse energy of 200µJ to remove the greatest volume of material as possible with each pulse. The pulse energy had been kept low previously in an attempt to avoid unnecessary collateral damage and keep the trench width as narrow as possible. It was found however that even at slow scanning speeds the unwanted damage was negligible.

The scanning speed of the beam was varied from 10mm/s (5, 2, 1, 0.5, 0.2, 0.1, 0.075) to 0.05mm/s to find the most effective speed for cutting through the wafer. Two other pulse energies of 120µJ and 160µJ were tested to provide a comparison to the 200µJ test. Figures 3.11(a) and (b) show the results of the experiment. It was found that a speed of 0.5mm/s produced cuts fully through the wafer after 4 passes, reducing the estimated time to cut a 5 finger 3mm comb to 4.6minutes.

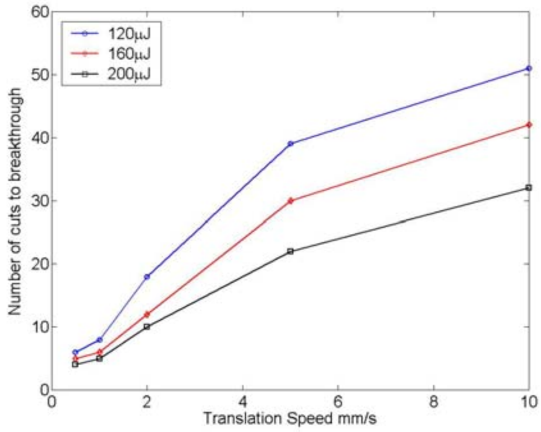

Figure 3.11 Number of beam passes required for breakthrough at varying cut speeds

It was found that the step in the z direction between each pass of the laser was unnecessary at the higher pulse energies, the same depth and quality of trench was produced with the focus unaltered throughout the test.

4. Machining quality

4.1 Inspection technique

Once the full depth of the wafer could be cut reliably, the next stage of development was to examine the edges of the cut that would make up the device, improving the quality (i.e. reducing the roughness) of these surfaces was necessary to produce a device that is low loss as the beam passed through the 10 or so joins in the comb.

The quality of the edge of the cuts was inspected with an optical microscope and an environmental scanning electron microscope (SEM). The procedure that was followed to expose the face of a cut was to cut a small section from a length of GaAs overhanging a glass substrate. The exposed ends, shown pictorially in Figure 4.1 could then easily be analysed under the microscopes available to us.

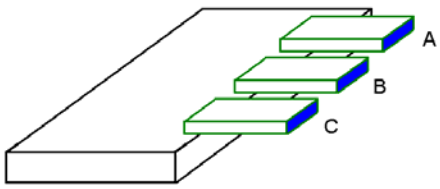

Figure 4.1 Exposed edges of GaAs

Initial examinations of the cut edges suggested that the surface roughness was poor for launching visible light through, but may have transmitted light at a wavelength of 10.6µm. The micrograph in Figure 4.2(a) (below) shows the surface exposed by machining and Figure 4.2(b) shows a SEM image of the same surface.

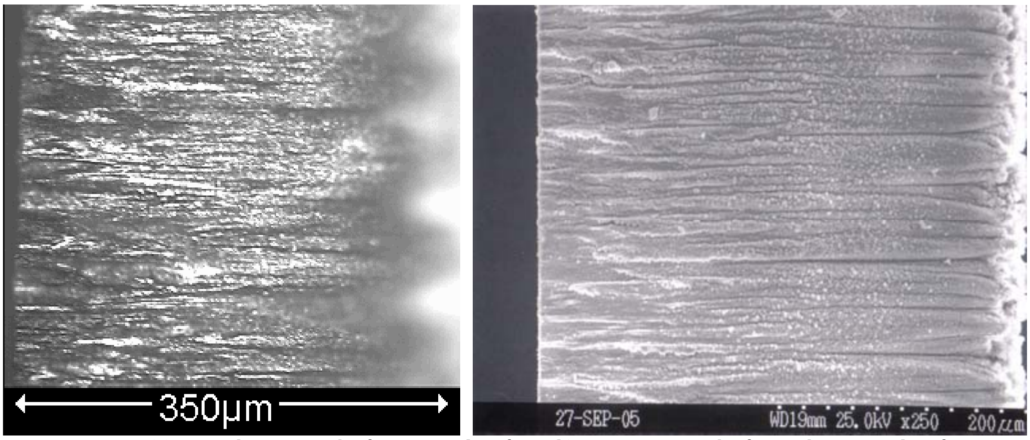

Figure 4.2(a) Optical micrograph of an exposed surface (b) SEM micrograph of a similar exposed surface

4.2 Effect of focal position

In an attempt to reduce the roughness of the machined surfaces a number of different parameters were altered. Firstly the position of the focus of the beam was altered for different samples. The position of the focus was kept constant for the duration of the cuts as investigated previously in section 3.2, but altered for different tests.

The first focus was upon the surface of the sample ($z=z_0$), the second 180µm ($z=z_0$-180µm) inside the wafer the third 360µm in, the fourth was 540µm and the fifth 720µm. The SEM micrographs of the best of the results are shown below in Figure 4.3(a)-(c).

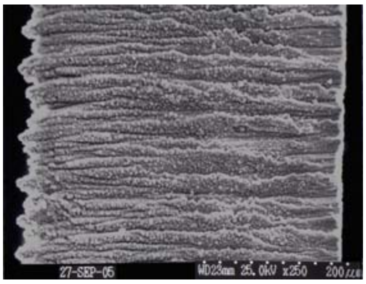

Fig 4.3(a) $z=z_0$

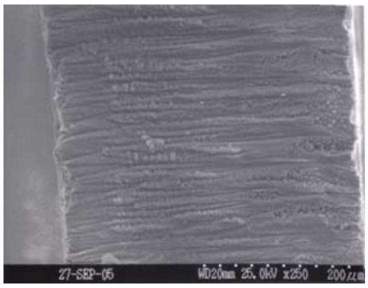

Fig4.3(b) $z=z_0$-180µm

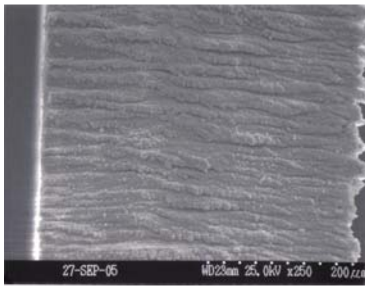

Fig 4.3(c) $z=z_0$-360µm

From examining these pictures it was decided to machine future samples at a focal positions of $z=z_0$-180µm to achieve the best machining. This position corresponds to placing the focus at approximately equal distances from the front and back wafer faces.

4.3 Polarisation of beam.

It has been reported that when a linearly polarised laser is used for machining of a trench, the relative orientations of the polarisation and the beam scanning direction affect the quality of the cut [2]. We studied the machining outcome of three different polarisations two linear, and one circular. The linear polarisations were orthogonal and perpendicular to the direction of the cut. From the SEM micrographs shown below in Figure 4.4 it was decided that orthogonal polarisation resulted in the best quality surface.

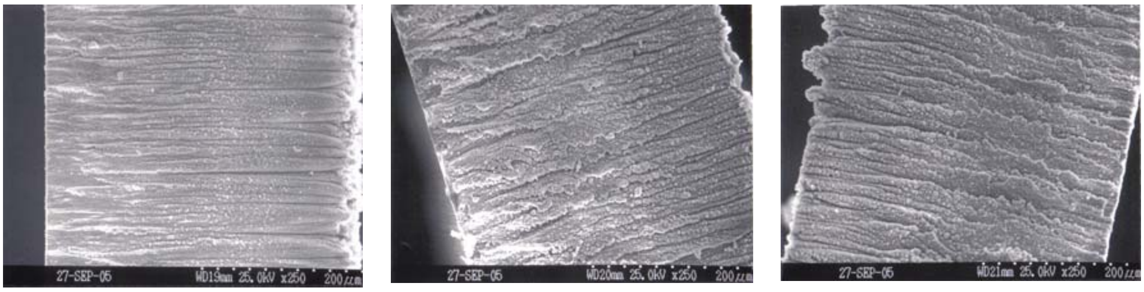

Fig4.4 Images of machined faces produced using (a) orthogonal, (b) circular and (c) perpendicular polarisations

4.4 Effect of wafer orientation

Due to the design of the QPM device, all of the cuts for the final structure have to be made at 45° to the major axis of the lattice, as the nonlinear process depends upon the wafer orientation. Since GaAs wafers will only cleave along the major and minor axes, all the tests so far have been carried out along either the major or minor axes of the wafer. It was deemed prudent to check that these tests are of a comparable quality to identical tests at ±45° to the major and minor axes. Machining tests were carried out at a pulse energy of 200µJ and a focal position of $z=z_0$-180µm and a scan speed of 0.5mm/sec. Tests were carried out at both 45° and -45° angles to the major axis. The results are shown below in figures 4.5(a) and (b) compared to an identical test along the axis shown in figure 4.5(c).

The results indicate that the machining quality obtained when machining at 45° and -45° to the major axis was comparable to previous results obtained with machining along the major axis.

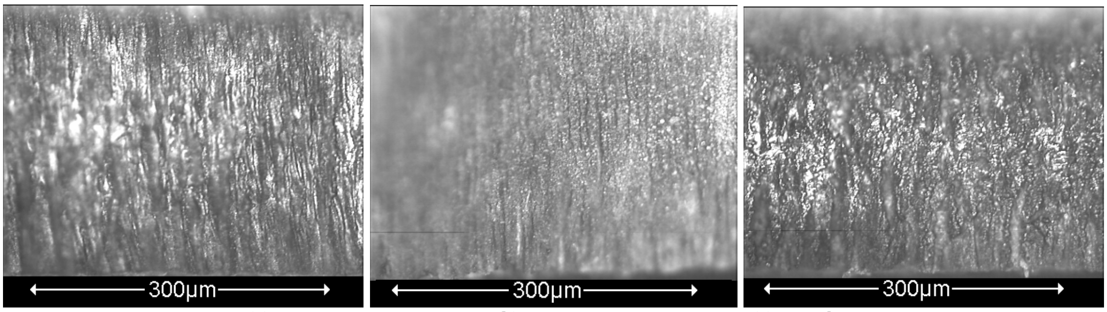

Figure 4.5(a) Cut at 45° to major axis; (b) Cut at -45° to major axis; (c) Cut along major axis

4.5 Effect of scanning speed

The scanning speed of 0.5mm/second was chosen previously to achieve high-efficiency cutting of the wafer, however it was necessary to independently determine which speed produced the best quality faces. The tests were made with an orthogonally polarised beam with a focus 180µm into the wafer, the speed was, as before, varied between 10mm/sec and 0.05mm/sec (5, 2, 1, 0.5, 0.2, 0.1, 0.075) and the pulse energy was kept at 200µJ. An optical microscope was used to analyse the surface quality of the channel walls and this is sufficient to see the quality difference that occurs between the individual experiments. Micrographs of the samples are shown in Figure 4.6(a)-(i), the scale in each of the pictures is identical, the wafer being 350µm wide.

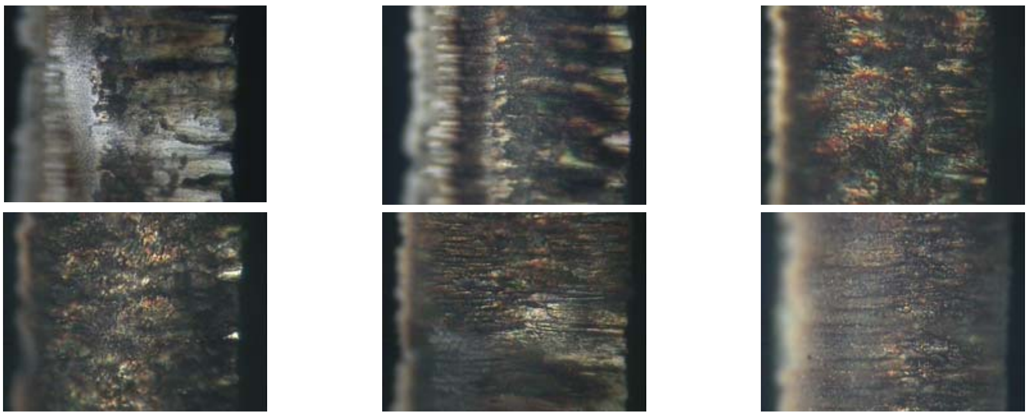

Figure 4.6 Exposed surfaces machined at rates of (a) 10mm/sec (b) 5mm/sec, (c) 2mm/sec, (d) 1mm/sec, (e) 0.5mm/sec, (f) 0.2mm/sec, (g) 0.1mm/sec, (h) 0.075mm/sec and (i) 0.05mm/sec

From these pictures it was determined that a scanning speed of 0.1mm/sec produced the best results and although this is slow to produce a device, the quality of the resulting cut makes this worthwhile.

5. Machining Shapes

Once all of the parameters for machining the GaAs wafers had been optimised several designs were produced, written in the code for commanding the motion control stages (Newport ESP M-ILS CCHA). The first test design was a single finger of thickness equal to one coherence length for the SHG at 10.6µm. All of the structures described in this section were machined with the optimal machining parameters given in Section 4.

5.1 Single fingers

The single finger was designed to be 137µm wide (one coherence length at λ=10.6µm), 350µm deep (wafer thickness) and 3mm long. The machining parameters were set to the optimal values as discussed in the previous sections. Figures 5.1 show four typical examples of the machined single fingers.

Figure 5.1 Typical single fingers of GaAs

When examining the machined samples it was noted that the fingers had a vertically tapered profile, arising from the Gaussian shape of the machining beam as it was focused into the sample, however this taper only extended to a depth of 100µm, resulting in 250µm of the exposed face being parallel. This is shown schematically in figure 5.2(a). An optical micrograph of the end of one of these single fingers is shown in figure 5.2(b).

Figure 5.2(a) schematic of finger with vertical taper and (b) micrograph showing actual taper

5.2 Multiple fingers

The single fingers that were machined proved that the material was robust enough to survive the shock associated with femtosecond machining and a design was created with the purpose of producing a comb structure with five fingers. Figures 5.3(a)-(d) shows SEM micrographs of a 5 finger comb with 50:50 duty cycle of 137µm and therefore a period of 274µm.

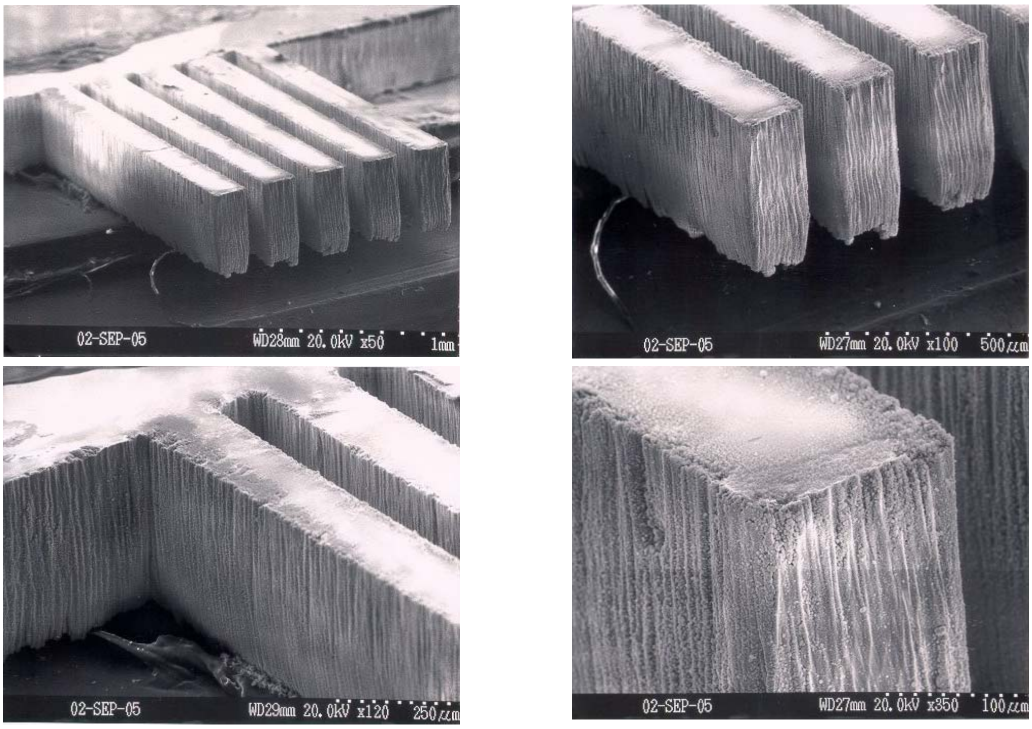

Figure 5.3 SEM micrographs of combs created by femtosecond machining (various magnifications)

The overall structure of the comb was very satisfactory with the corners inward and outward being extremely uniform and sharp at 90° following the design exactly.

5.3 Tapered combs

To mesh the combs together to produce a device, a taper was required in the fingers of each comb to avoid breaking them while meshing together. The comb program was modified to include a taper of angle 1.5° in the fingers (retaining a width half way along each finger of 137μm and a duty cycle of 50:50) and several tapered samples were machined. An example of one of these tapered combs is shown in Figures 5.4(a)-(d). The fingers were 3mm in length with a period of 274μm.

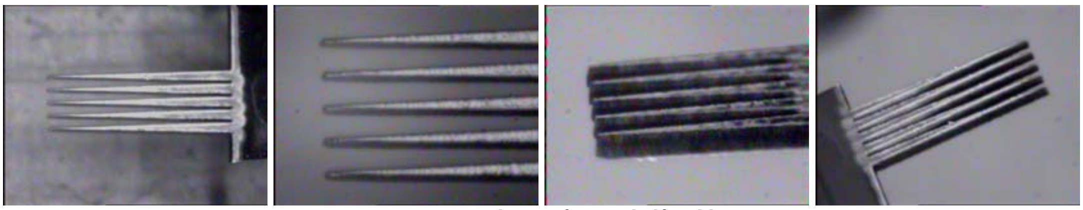

Figure 5.4 Tapered GaAs fingers, half-width 137μm

The final step in the manufacturing process was to mesh two combs together as shown in Figure 5.5 to form a composite GaAs device of a design compatible with achieving a QPM interaction. For this task two x-y-z translation stages were purchased, each with a camber and a rotation degree of freedom to provide maximum manoeuvrability of the individual combs. Two combs were successfully meshed together with no visible structural damage, creating a tightly fitting sample as shown in the optical micrographs in Figure 5.5 below.

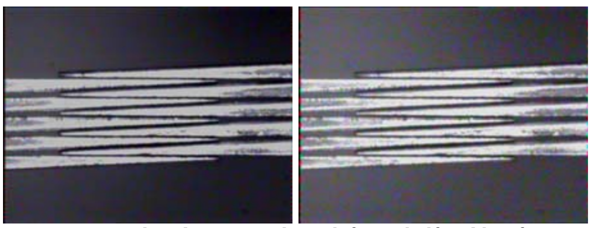

Figure 5.5 Interlaced GaAs combs with finger half-widths of 137μm

The shadows created between the fingers of opposing combs are due to the vertical taper mentioned in Section 5.1, however due to the planar nature of the finger further down, they mesh together as desired out of view of these optical micrographs.

6. Optical testing of machined GaAs samples

6.1 OPO testing

To test the transmission of the cut faces of the wafer a single finger sample was put into the focus of a high quality mid-infrared OPO idler beam at a wavelength of 2.3µm. As discussed in Section 2 the initial prototype structure was constructed with the aim of frequency doubling light at a wavelength of 10.6µm. Because of the superior quality of the OPO beam compared to a CO_2 laser, it was decided that the transmission of the λ=2.3µm beam should be used as a benchmark test for a sample's quality before being taken to further tests. A section of untouched wafer was tested for transmission and found to be acting as expected with a ~30% reflection loss from each face, but the machined sample showed no real transmission with an negligible overall 0.4% transmission. This poor transmission is probably attributed to the surface roughness of the machined faces which has a depth comparable to the 2.3µm wavelength of the mid-IR OPO. Another possibility is that the exposed faces of the GaAs are covered in debris such as oxides which absorb in the mid-IR. Due to the non-thermal nature of femtosecond machining we expect that the most likely cause is surface roughness, rather than debris.

6.2 CO_2 testing

Once the meshing of the tapered combs had been successfully completed, several samples of the mesh and of the single finger were taken to be tested with a CO_2 laser made available to the group by the power photonics group at Heriot Watt University. The CO_2 laser, operating at a wavelength of 10.6µm was a pulsed laser with variable repetition rate but typically ran at 10Hz. The pulse duration was a minimum of 100µs but could be chopped extra-cavity by an acousto-optic modulator (AOM) to durations of less than 5µs. Due to the non-linear nature of the experiment, the peak power of the pulse was required to be high, and due to the thermal nature of CO_2 laser absorption the average power had to be kept low to avoid damage to the material.

A schematic of the experimental setup is shown in Figure 6.1, opposite.

The spatial filter gave a circular beam with which to work, the sapphire filter absorbed the unconverted light at λ=10.6µm and was transparent to light at λ=5.3µm. A bulk section of wafer was initially included in the apparatus to ensure that the fluence of the laser was not high enough to machine the samples, and also to check the transmission of the GaAs.

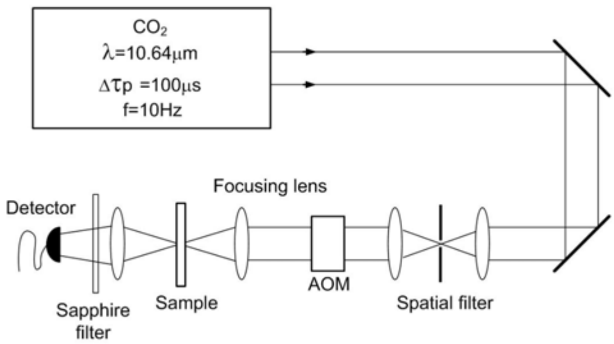

Figure 6.1 schematic of CO_2 laser test.

A previous CO_2 laser machining study was carried out with silicon [3], a material very similar to GaAs being high refractive index and similar in mechanical and thermal properties. In this study the threshold fluence was found to be 280kW/cm^2, and it was decided to keep the laser fluence below this threshold. For our experiments the lens employed to focus the beam through the device was a 38mm focal length singlet, capable of producing a focal spot of radius 51µm in air. Aiming to keep the fluence below 200kW/cm^2 it was necessary for us to keep the peak power of our beam below 16.34W to avoid machining.

The range of peak powers chosen, from 15W to 3W would all leave the wafer untouched, no machining or damage was visible with a pulse duration of 10µs for long exposures of radiation. However, when the wafer was replaced with a machined sample of a single finger exposure to any of the powers tested resulted in machining upon the surface of the sample. This machining was unexpected because GaAs is transparent at 10.6µm therefore the surface may have been contaminated with debris that absorbed at this wavelength and led to local heating and effective machining of the GaAs.

6.3 Conclusions from optical tests

After testing the samples both with laser beams of λ=2.3µm and λ=10.6µm and having had no success with either it led us to believe that one or both of two things caused this. First that the surface roughness of the cuts was too severe to allow transmission and resulted in excessive optical scattering. The second possibility is that oxides of Ga and/or As were formed on the surface during machining which were not transparent to either wavelength. Whatever the cause, there was absorption on the surface of the cut and machining with the CO_2 beam occurred.

7. Further work: post processing for improving optical quality

In an effort to propose solutions to the problems we have encountered we have created a list of what we believe are workable ideas to produce a device with smoother surface finish since mechanical smoothing methods are not viable with such a delicate structure.

7.1 Chemical smoothing

Smoothing the surface of the cut with sulphuric acid is an attractive possibility for producing more transparent devices, the sulphuric acid should preferentially attack any protruding structures and cause less damage to depressions than smooth surfaces.

7.2 Furnace heating for smoothing and removing oxides

7.2.1 Some smoothing is likely to occur at 70 to 80% of the melting temperature (Mp=1240°C) which should be done under an inert atmosphere to prevent oxidation problems. We would be able to do this on campus, as we have a suitable furnace (up to 1500°C). It would be wise to check the phase diagram of the material to check whether there might be some changes to the bulk crystal structure, but discussions with members of the MBE research group at Heriot-Watt lead us to believe there should not be a problem with crystal structure deformation.

7.2.2 If, as previously hypothesised there exists a layer of oxides on the surface of the cut, a short exposure in a furnace at a more modest temperature of ~700°C could be used to remove these oxides, as is done in the MBE production process.

7.3 High index glasses melted into gaps

The aspiration behind this project was to tailor-make two structures which could be easily and quickly joined together to form a working device. We have considered the idea of using a Chalcogenide glass as a high index index-matching material. We believe this idea to be quite feasible through existing contacts; Prof Angela Seddon at Nottingham University "we have made high index glasses - perhaps, so far, up to ~3.4, certainly above that of GaAs. Their Tg would be ~160°C". In this case we could heat up a "blob" of glass on top of the interlaced comb structure, and let it flow into all the gaps, and over the outside faces. This would hopefully result in the complete structure being fused inside a piece of glass, the end-faces of which could be polished to give good optical coupling and an extremely robust device. The heating would need to be done in a fume cupboard, as the glasses typically contain As. This technique could also be used with a single comb to create a QPM structure.

[1] AN Pikhtin et al Sov. Phys. Semiconductors V12 P622 (1978)

[2] K Venkatakrishnan Jnl. App. Physics V92 N3 P1604 (2002)

[3] F Villareal (HWU) Study for internal use only (2001)